Progress in Safety and Environmental Aspects of Inertial Fusion Energy at Lawrence Livermore National Laboratory*

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Significant progress has been made at LLNL in our study of the safety & environmental issues related to IFE

- Safety assessments
- Driver-chamber interface
- Target materials
- Fast ignition
- Collaborations
- Future work

We are developing safety assessments for IFE power plant designs

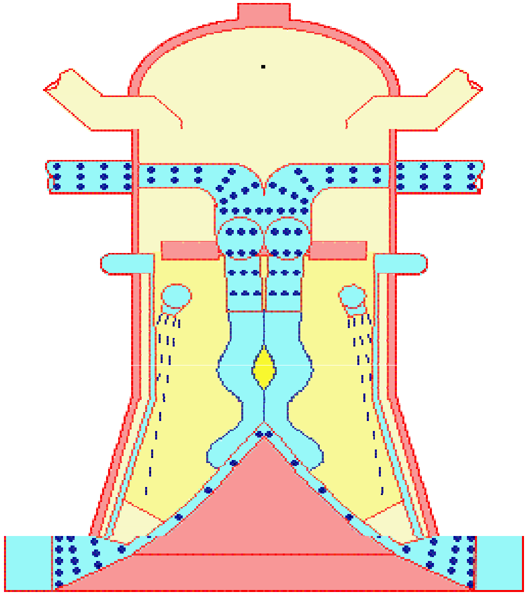
- We have adopted and adapted state-of-the-art codes to study off-normal plant conditions and potential radioactivity releases to the environment

- CHEMCON heat transfer code:
  - Used to simulate long-term time-temperature histories of different components during thermal transients
  - Oxidation package modified for enhanced representation of graphite oxidation in case of air/steam ingress

- MELCOR thermal hydraulics code:
  - adapted for fusion applications by INEEL fusion safety program
  - used to model thermal-hydraulics and aerosol and fusion products transport and release

Safety assessment: HYLIFE-II

- Severe loss-of-coolant accident analyzed:
  - Loss of all Flibe coolant
  - Simultaneous break of all beam tubes
  - Breeches in inner shielding wall and confinement building (1 m^2) provide pathway for release
- The DOE Fusion Safety Standards set an off-site dose limit of 10 mSv (1 rem) to avoid need for an evacuation plan
- We assume typical weather conditions:
  - Class D atmospheric stability; 4 m/s wind speed
  - No thermal plume rise and inversion layer at 250 m
  - Ground-level release and site boundary at 1 km
  - Initial building wake set to 100 m wide by 50 m high
  - No precipitation



HYLIFE-II

Safety assessment: HYLIFE-II (cont'd.)

- There are four main sources of radioactivity:
  - Each target vaporizes ~ ***10 kg of Flibe***. Although we assume a total LOCA, we conservatively include this Flibe aerosol and its activation products.
  - ~ 140 g of tritium would be trapped within the chamber, blanket, and piping. We assume that entire tritium inventory is converted to the more radiotoxic HTO form, yielding a mass of ~ ***1 kg of HTO***.
  - We account for a 1-y inventory of corrosion products (1 μm/y corrosion rate assumed). This leads to a SS304 inventory of 8.3 kg.
  - INEEL oxidation experiments on PCA give an additional 0.5 kg of SS304 for our temperatures. Adding this to the 8.3 kg of corrosion products, we have ~ 10 kg. Scaling by the mass of Flibe present in the chamber, we obtain ***0.5 kg of SS304***.

Safety assessment: HYLIFE-II (cont'd.)

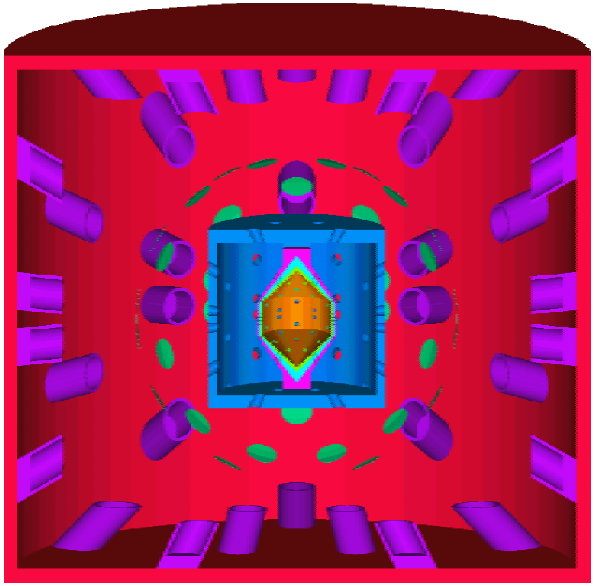
Radioactive source	Mobilized mass/activity	Release fraction	Dose at site boundary
SS304 corrosion/ oxidation products	0.5 kg / 1.3×10^{12} Bq	11%	3.0 μSv / 0.3 mrem
Vaporized Flibe	10 kg / 7.1×10^{15} Bq	12%	42 μSv / 4.2 mrem
HTO trapped in steel structures	1 kg / 5.0×10^{16} Bq	86%	4.3 mSv / 430 mrem

A HYLIFE-II site boundary dose of 4.3 mSv (0.43 rem) implies that an evacuation plan would *not* be needed

Safety assessment: Sombrero

- We are developing accident scenarios for the Sombrero power plant design

- Preliminary results reveal key issues:
  - Carbon composite (C/C) chamber may rapidly burn when exposed to air or steam
  - Original design study estimated tritium retention of only 10 g within C/C–we assume a C/C tritium inventory of 1 kg based on recent neutron irradiation studies
  - Xe atmosphere (~ 70 Pa), which protects the first wall, may pose significant radiological hazard–it was ignored in previous work (Kr may be a less hazardous substitute)



Sombrero

Safety assessment: Sombrero (cont'd.)

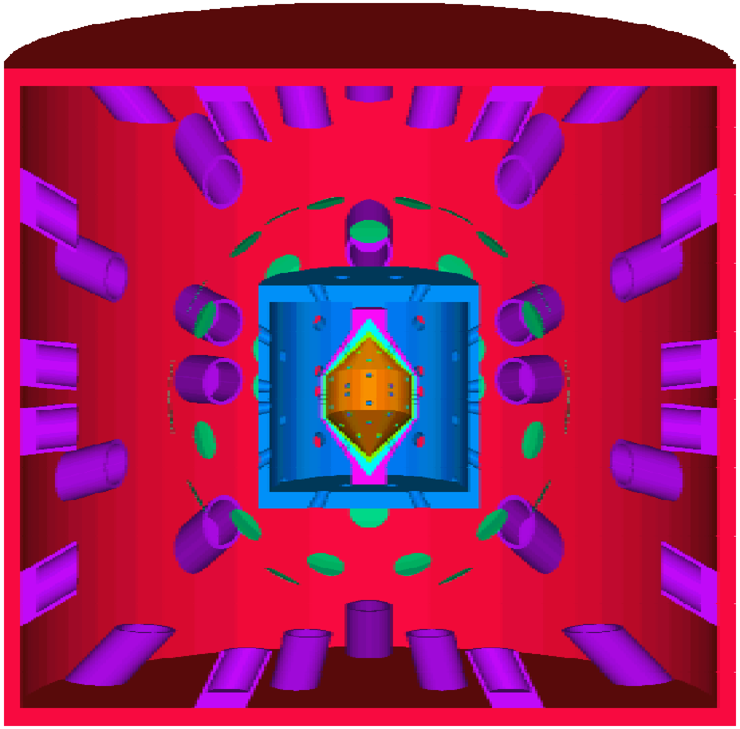
- We consider a severe accident scenario consisting of loss of vacuum/loss of flow with simultaneous failure of the confinement building
- CHEMCON simulates long-term thermal transient due to graphite oxidation and radioactive decay heat
- MELCOR simulates thermal-hydraulics, heat transfer, aerosol physics and fusion product release and transport
- For a modified Sombrero using Kr, we calculate a dose of 8.3 mSv (830 mrem)─a total tritium inventory of 1.9 kg can be tolerated in this case
- Design using Xe would lead to a dose of 9.5 mSv (950 mrem) if the non-xenon activation products can be removed or 54 mSv (5.4 rem) if the iodine and cesium are included in the release

Sombrero site boundary doses of 8.3 or 9.5 mSv would *not* require an evacuation plan

The driver-chamber interface is an active area of S&E study

- Important issue for both laser- and heavy-ion-driven designs:
  - Laser designs need to protect final optical component (sits *in* line-of-sight) and focusing mirror (sits just *out* of line-of-sight)
  - Heavy-ion designs need to protect final focusing magnets
- Radiation damage lifetimes make the driver-chamber interface an important environmental issue:
  - Damaged components could comprise a significant waste stream
  - Not all components (e.g., NbTi or Nb_3Sn superconductors) would qualify for disposal via shallow land burial
- Down time for component replacement would negatively impact economics, plant availability, and occupational exposures

Driver-chamber interface: lasers



- Radiation damage to the final focusing system is a key issue in a laser-driven IFE power plant.
- A detailed, 3-D model of Sombrero was developed to calculate neutron and γ-ray fluences and doses in the focusing mirrors and final optical components
- Variations of model created for open solid-angle fractions of 0.25% (from published report) and 5% (increased to maximum that might be needed for DPSSL driver)
- Grazing incidence metal mirrors (GIMMs), used as the final optical components in the original report, were replaced with transmissive fused silica wedges

Driver-chamber interface: lasers (cont'd.)

- Neutrons scattered off of the final optical component (wedge or GIMM) dominate the fast neutron flux at the focusing mirrors:
  - Relatively sensitive focusing mirrors may have fast neutron fluence limit of only 10^{18}-10^{19} n/cm^2 leading to a lifetime of only 0.25-2.5 FPY

- Final focusing mirror dose rate is dominated by neutron-induced gamma-rays:
  - 4 Gy/s at mirror location (200× higher than neutron dose rate)
  - Recent work[1] shows that γ-ray dose is important for transmissive optics–can this also be an issue for mirrors?

- Wedge/GIMM sits in line-of-sight; is subjected to much higher levels
  - Fast neutron flux at the wedge/GIMM location is 9.5×10^{12} n/cm^2-s
  - Yields wedge/GIMM lifetime of 0.33-33 FPY for 10^{20}-10^{22} n/cm^2 limits

[1] C. D. Marshall, J. A. Speth, S. A. Payne, Induced optical absorption in gamma, neutron and ultraviolet irradiated fused quartz and silica, *J. of Non-Crystalline Solids* **212** (1997) 59-73.

Recent accelerator designs allow less space for shielding

- Previous HIF power plant designs, such as HIBALL and Osiris, used only 12-20 beams:
  - Allowed 30-40 cm of shielding on the inner bore of each magnet
  - Magnets could last for lifetime of power plant

- Today's accelerator and final focus designs[1-3] are using a greater number of beams (48-192 and beyond):
  - Reduces space charge and accelerator cost
  - Only 3-5 cm of shielding has been allocated
  - Radiation shielding, magnet cooling, and neutron activation issues are more severe

[1] J. J. Barnard et al., "Induction accelerator architectures for heavy-ion fusion," *Nucl. Inst. and Meth. A* **415** (1998) 218-228.

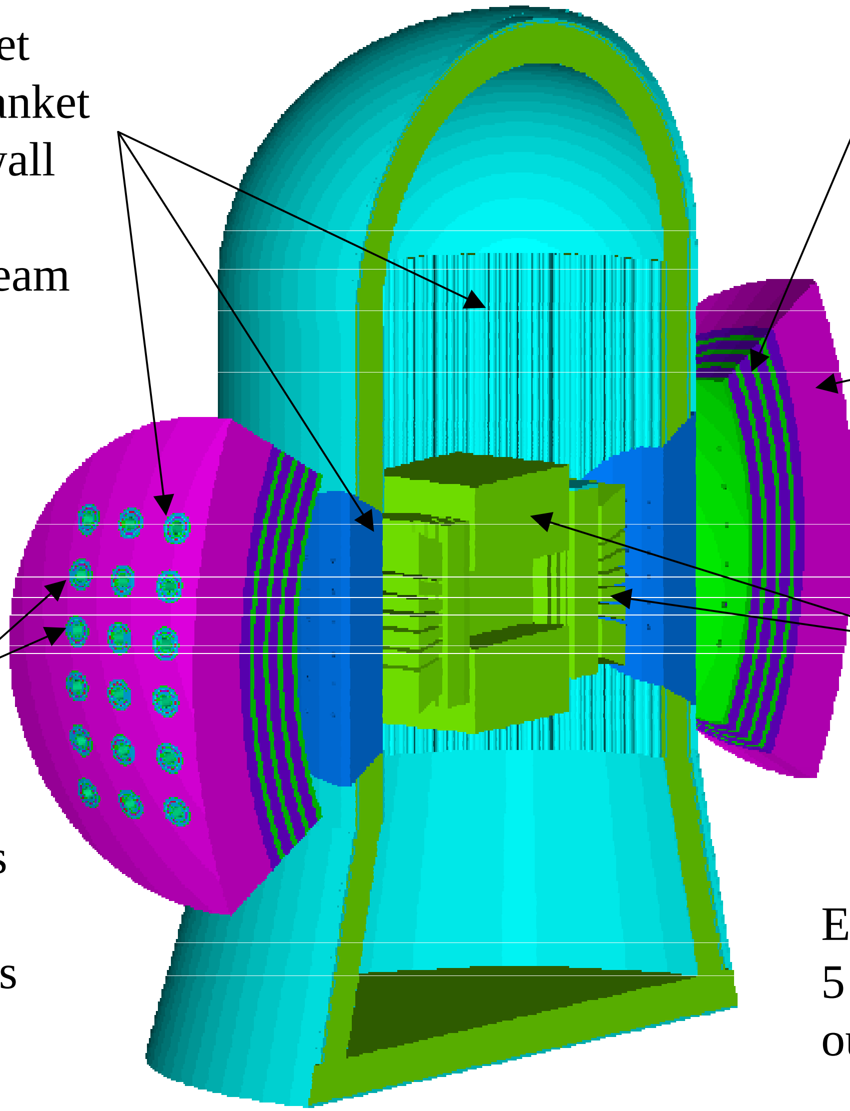
[2] W. R. Meier, R. O. Bangerter, and A. Faltens, "An integrated systems model for heavy ion drivers," *Nucl. Inst. and Meth. A* **415** (1998) 249-255.

[3] P. A. House, "Beam line and first vessel wall shielding in HYLIFE-II," Lawrence Livermore National Laboratory, UCRL-ID-136107 (Oct. 1999).

Multiple shielding features are needed to extend the magnet lifetime to 30+ years

HYLIFE-II target chamber and blanket including first wall tubes, shielding block, and 36-beam magnet arrays

Layered, shielding in front of magnet arrays



Shielding "egg-crate" surrounding magnet array

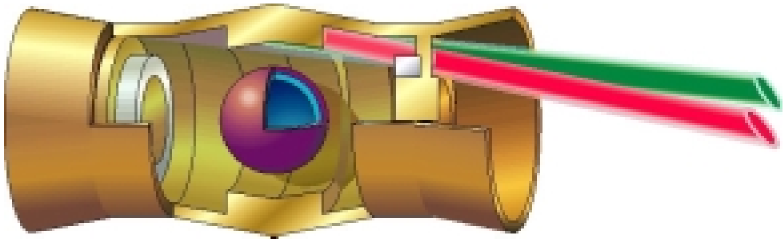
Protective Flibe pocket and cross jets

A larger than minimum angle between rows & columns reduces "cross-talk" between magnets

Each magnet uses 5 cm each of inner and outer bore shielding

Selection of target materials has important S&E implications

- Target materials need to be:
  - Recyclable in a timely fashion to provide a low waste stream ("once through" method would use ~ 100 tons per year)
  - Disposable via shallow land burial (SLB) upon ultimate disposal
  - Acceptable accident dose (assuming conservative release fractions)

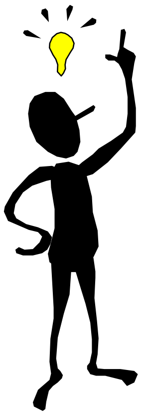


Close-Coupled Heavy-Ion Target Design

- Survey of 264 stable isotopes from Li to Po was completed:
  - 138 isotopes met dose rate criterion (recycling)
  - 176 isotopes met SLB criterion
  - 97 isotopes simultaneously met the dose rate and SLB criteria
  - Of these 97 isotopes, 48 met the accident dose criterion as well
- Several elements, such as Pb, would require little isotopic separation (only ^{204}Pb at 1.4% of natural Pb needs to be removed)

Fast ignition offers a step-change in the pursuit of inertial fusion energy (IFE)

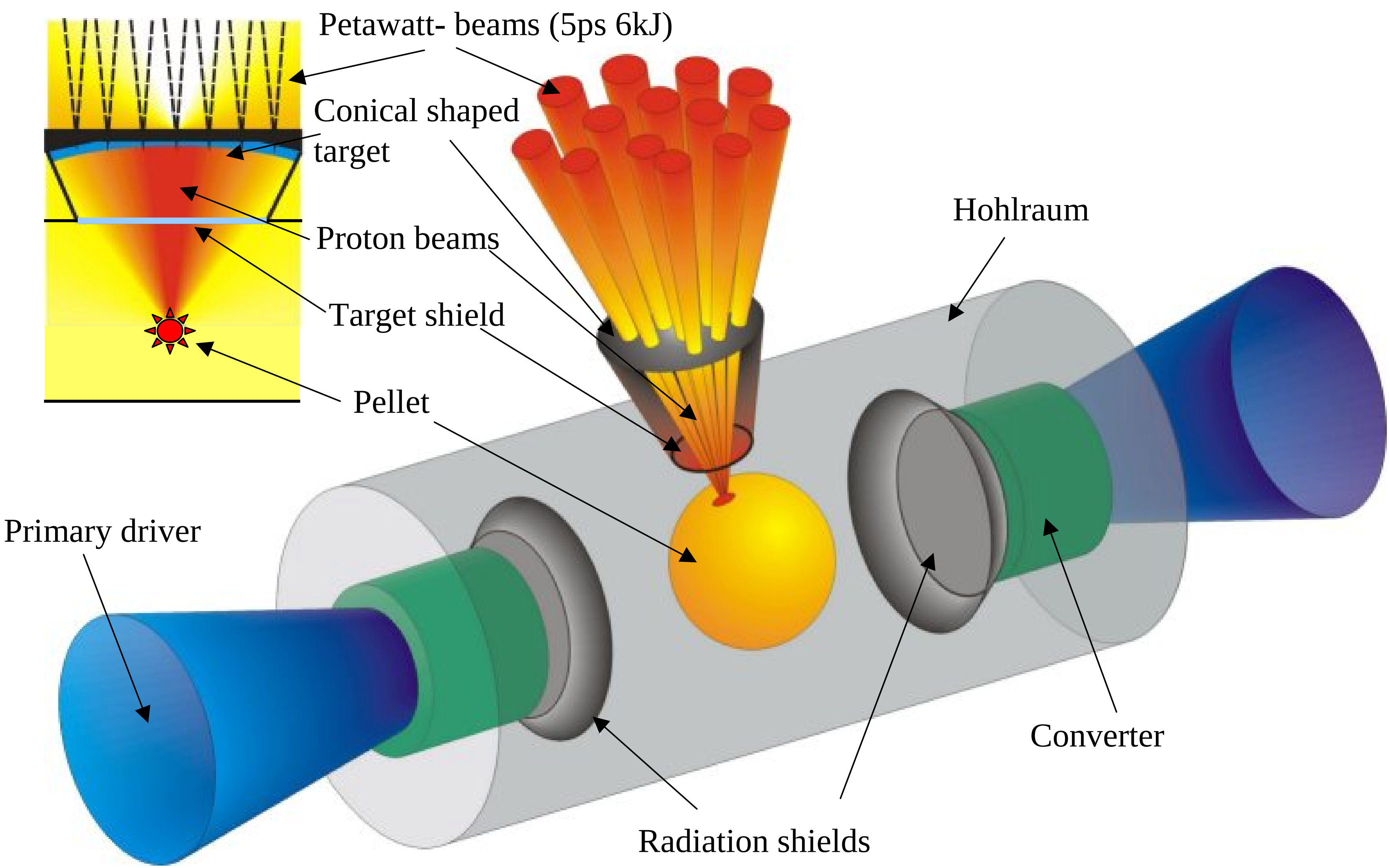
- Reduction in total driver energies, driver cost, and cost of electricity (COE)
- Reduction in radiation damage rates
- Possibility to use advanced targets:
  - Reduce or eliminate need for breeding blankets
  - Exceptional safety & environmental characteristics
- Relaxation of target fabrication requirements



Fast ignition is expected to open the parameter space for ***innovation*** in chamber design (materials and configuration) and power conversion system design.

Fast ignition could be used with a variety of target designs

- Moving from central, hot-spot ignition to fast ignition, total driver energy falls from 3-5 MJ to ***< 1 MJ***
- Could hold driver energy constant and reach higher yields
  - Repetition rates could be reduced from ~ 5 Hz to only 1-2 Hz
  - Wider range of available targets increases design ***flexibility***
- Tritium-lean targets would operate at ρr of 10-20 g/cm^2 and have overall tritium percentages as low as 0.5%
  - Main fuel would be D; sparkplug region, which the ignitor beams strike, would contain 20-50% T
  - Due to high ρr and low tritium inventories, ***targets may be self-sufficient from tritium breeding perspective***
- Other advanced fuels might include $B_2D_3T_3$, which melts ***above liquid nitrogen temperatures***



Petawatt- beams (5ps 6kJ)
Conical shaped
target
Proton beams
Target shield
Pellet
Hohlraum
Primary driver
Converter
Radiation shields

Collaborations are a key part of our work on IFE S&E issues

- UNED/Instituto de Fusion Nuclear in Madrid:
  - ACAB code and libraries for detailed analysis of neutron activation in fusion systems
  - Dose conversion factor libraries (generated from MACCS2) for calculation of doses from radiological releases

- INEEL:
  - Fusion-modified version of the MELCOR code for thermal hydraulics and aerosol transport calculations
  - CHEMCON code for oxidation and heat transfer calculations
  - Extensive experience using the above codes and development of accident scenarios
  - Data on oxidation-driven mobilization and chemical reactivity of various materials

Future work in IFE S&E

- We plan to complete our analyses of HYLIFE-II and Sombrero accident scenarios
- Accident analyses for baseline target fabrication facility are underway
- Codes are being modified to analyze more aggressive (clearance based) waste management philosophy
- We hope to expand our efforts in fast ignition; Some of LLNL's target design work is devoted to fast ignition
- New collaboration with the ARIES Team begins in June with study of IFE systems
- Support of Integrated Research Experiment design for heavy ions; determine if the IRE can answer S&E questions